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Measurement of the energy of alpha-, beta-, and gamma-rays by means of a scintillation counter

By Sven A. E. Johansson

With 11 figures in the text

Ionizing particles are registered in a scintillation counter by the light flashes (scintillations) which arise from their passage through a luminescent crystal. These scintillations are recorded by a photomultiplier tube. An avalanche of electrons proportional in number to the photons in the scintillation are collected on the anode of the multiplier tube. With a suitable anode circuit time constant it is possible to obtain a pulse height proportional to the number of photons in the scintillation. The question now is in what manner the number of photons and thus also the pulse height are dependent upon the energy of the entering particle. If there is any simple relationship between pulse height and energy, it should be possible to use the scintillation counter for measuring this energy.

Broser and Kallmann[1] have demonstrated that if monoenergetic alpha-particles are allowed to strike the phosphor of a scintillation counter, the pulses obtained will all be of approximately the same height. By using alpha-particles of varying energy they were able to show the pulse height to be directly proportional to the energy. The scintillation counter can thus be used to measure the energy of alpha-rays. In the present paper[2] it will be demonstrated that the proportionality between pulse height and energy is also valid for electrons and that with a scintillation counter it is possible to measure with satisfactory accuracy the energy of beta- and gamma-rays.

Apparatus

Fig. 1 shows a diagram of the apparatus employed. As the phosphor thallium-activated sodium iodide was used. The phosphor was made according to Kyropoulos'[3] method. Sodium iodide and 0.03 per cent of thallium nitrate were melted in an electric furnace. A quartz tube sealed at one end was dipped into the melt. When the quartz tube was cooled with compressed air, a crystal of sodium iodide was formed at the tip of the tube. In this manner fairly large crystals with good transparency are obtained. The phosphor used in the present investigation is cylindrical, 3 cm in diameter and 1.5 cm thick. When studying the energy conditions in the absorption of the beta- and gamma-rays in the phosphor it is of great

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[1] I. Broser, H. Kallmann, Nature *163*, 20 (1949).

[2] A short account of this work was given at the Conference of the Swedish National Committee of Physics, Sept. 1949.

[3] S. Kyropoulos, Z. Anorg. Chem., *154*, 308 (1926).

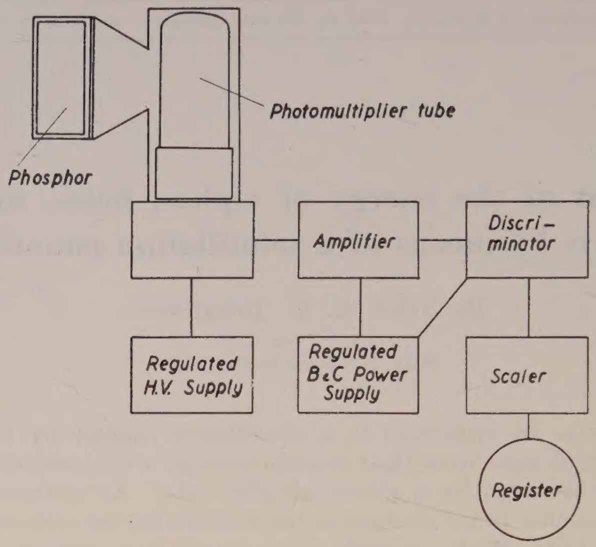

Fig. 1. Schematic diagram of scintillation counter.

importance that the phosphor employed is not too small. Electrons with energies greater than 1 MeV have a range of several millimeters in the phosphor. If rays of high energy are examined with a small phosphor, a considerable part of the electrons will pass through the phosphor. Thus, they do not give up all their energy, and this fact naturally influences the results.

Sodium iodide is extremely hygroscopic. A crystal of sodium iodide is rapidly discolored in the atmosphere, thereby becoming less efficient. The crystal is therefore hermetically enclosed in a container, one side of which is composed of a perspex plate so that the light can reach the photomultiplier tube.

A scintillation counter has a comparatively high background, which comes from the photomultiplier tube. The photo-cathode and dynodes emit electrons even in complete darkness. The electrons emitted from the photo-cathode and the first dynodes are sufficiently amplified in the multiplier to give pulses of noticeable height. In order that the pulses from the scintillations shall not disappear in the background at a low counting rate, they must be of sufficient height so that they can be distinguished from the background by means of a pulse height discriminator. A good photomultiplier tube has approximately 10 pulses per second of greater height than that of 5 photoelectrons.[1] With an efficiency of 5 per cent for the photo-cathode this height is equivalent to a scintillation of 100 photons. One must therefore use a phosphor which transforms a large part of the entering energy into light and concentrates the greatest possible amount of this light upon the photo-cathode. As shown in fig. 1 the crystal container is connected to the casing of the photomultiplier tube by means of a conic funnel. In the tip of the funnel there is an opening just opposite the photo-cathode, of the same shape and size as the cathode. The crystal container and the funnel are painted on the inside with magnesium oxide which has a very good reflecting power. Part of the light emitted from the phosphor is absorbed during the repeated reflections against the walls but the greater part reaches the photo-cathode through the opening of the funnel. With a good phosphor and an effective light collection the background is negligible in a counting of alpha-rays with an energy greater than 0.2 MeV. Beta- and gamma-rays give considerably smaller pulses than alpha-rays of the same energy. This is due partly to the fact that the efficiency of the phosphor is less for electrons than for alpha-particles and partly to the continuous energy distribution of the beta-rays and the Compton recoil electrons which are excited by the gamma-rays. For this reason the background can not usually be disregarded in a study of the pulses from beta- and gamma-rays. All measurements given on the following pages are corrected for the background.

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[1] G. A. Morton, J. A. Mitchell, Nucleonics *4*, No 1 (1949).

The photomultiplier tube used is of the type R. C. A. 1 P 21. The voltage of the cathode and dynodes is supplied in the usual manner by a voltage-dividing resistor network. The 10 resistors in the network are of 50 000 ohms each. The last four dynodes are bypassed through condensers in order to reduce the current surges through the resistors. The voltage of the photomultiplier has generally been 80 V per stage. The lower the voltage the more favourable the relation between the height of the signal pulses and the height of the noise pulses. The voltage, however, cannot be reduced too much as the gain in the multiplier decreases greatly with the voltage. At low gain a considerable statistical spread occurs, which cannot be allowed in measurements of the pulse heights. The multiplier is supplied with a well-regulated negative voltage at the cathode. In exact measurements it is essential that the variations in the voltage do not exceed 1 volt. The adjustment of the voltage and the control of its constancy is made by an accurate voltmeter.

The pulses from the multiplier are amplified in a linear two-stage amplifier with feedback and a cathode follower as the output stage. The gain can be altered by changing the feed back ratio. The plate voltage supply is well stabilized. The heater voltage is adjusted and controlled by means of a voltmeter.

The amplifier is followed by a discriminator. The latter consists of a Schmitt trigger circuit and the bias of the circuit can be adjusted by means of an accurate potentiometer. The voltage for the potentiometer and the plates in the trigger circuit is well stabilized in order to obtain satisfactory accuracy. A discriminator is only sensitive to pulses with heights surpassing a value set on the potentiometer of the discriminator. If the counting rate is measured as a function of the discriminator setting the integral bias curve is obtained, which thus gives the number of pulses with greater height for a certain pulse height. From the difference in the counting rate of two discriminator settings the number of pulses in the interval between the two settings is obtained. By measuring the counting rate of a number of evenly distributed discriminator settings and calculating the difference between adjacent values one obtains the differential bias curve which gives for a certain height the number of pulses in an interval around this height. In order to obtain a detailed pulse height distribution curve, however, the area to be measured should be divided into a large number of intervals. This division must not, however, be carried too far. The relative errors increase with the minuteness of the division.

The discriminator is connected to a scale-of-64 and the latter to a register. The counting rate is limited by the maximal rate of the register, which is about 30 pulses per second. If very high counting rates are desired another scaler can be introduced between the discriminator and the register.

If reproducible values are to be obtained it is essential that the experimental conditions are absolutely constant. Even changes in the resistances of the electronic circuits due to changes in temperature can produce marked variations in the measurements. In order to eliminate this source of error the apparatus is placed in a room with constant temperature. Disturbances from the surroundings may easily enter the apparatus by way of the power line, causing erroneous results. These disturbances are eliminated by means of a highfrequency filter between the line and the various power supplies. After these precautionary steps had been taken the apparatus showed very good stability. The measurements are reproducible within the limits of the statistical fluctuations. The figures reported in the following have usually been obtained several times and the results have always been consistent.

Alpha-rays

If a scintillation counter is used to measure the energy of ionizing particles, the pulse height must first be determined with a source emitting monoenergetic particles. Only when the pulse height distribution of the monoenergetic rays is known it is possible to interpret the pulse distributions obtained for rays with continuous energy distribution, as, for example, beta-rays. For these measurements the conditions are simplest for alpha-rays. It is possible to make a source, e.g., of polonium, which emits monoenergetic alpha-rays. On account of the short range, special care must be taken to avoid self-absorption in the source. Care should also be taken that the phosphor in the scintillation counter has a constant efficiency within the area affected by the alpha-rays. A fairly large, absolutely homogeneous crystal is most preferable. The surface must be well polished and cleaned. An X-ray screen or pulverized zinc sulfide is less suitable for the phosphor. Good results, however, can be obtained with transparent crystals of scheelite. A more satisfactory method is to melt the radioactive material to be investigated into a crystal of thallium-activated sodium iodide. A small amount of the sample is added to the melt and a crystal of sodium iodide is made as described above. Part of the sample is then incorporated in the crystal without affecting the homogenity or luminous efficiency of the latter. The alpha-particles are thus emitted within the phosphor so that the release of energy occurs under identical conditions for all alpha-particles.

Fig. 2 shows the distribution of the pulses obtained from the scintillation counter at various pulse heights when polonium is incorporated in the phosphor. This is the differential bias curve, that is to say, the number of pulses in a small pulse height interval is plotted against the middle point of this interval. The errors inscribed in this figure as in all following figures denote the calculated standard errors. It appears from the curve that the pulses are of essentially the same height. The symmetrical form of the graph indicates that the deviations from the mean are due to various statistical fluctuations. The number of photons emitted by the phosphor on the absorption of an alpha-particle varies. The probability of a photon reaching the photo-cathode of the multiplier is also subjected to statistical fluctuations. The efficiency of the cathode is rather low. Only 5 to 10 per cent of the photons reaching the cathode release a photoelectron and statistical fluctuations may occur here. Finally, the amplification in the multiplier is a statistical process. Measurements made by HOYT[1] show that the multiplier contributes only slightly to the spread if the number of photoelectrons formed is greater than 35. The spread, therefore, depends

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[1] ROSALIE HOYT, Rev. Sci. Instr. *20*, 178 (1949).

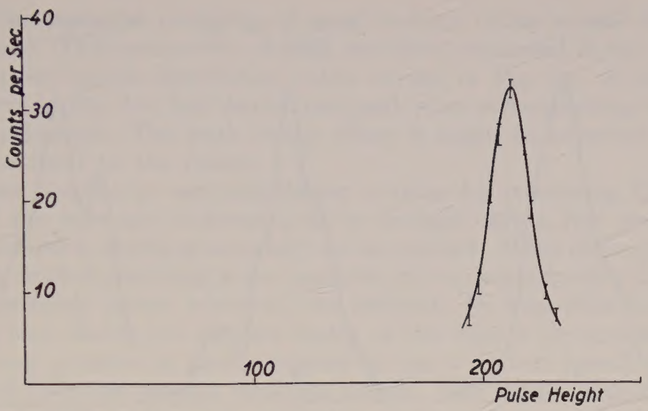

Fig. 2. Pulse height distribution curve for alpha-rays from polonium.

mostly on variations in the number of photoelectrons. The number of photoelectrons is easily calculated approximately in the measurement, as shown in Fig. 2. The peak in the pulse height distribution corresponds to a pulse height of 35 volts. The gain in the amplifier is 50. The multiplier has an anode capacity of 15 pF. From this the number of electrons collected on the anode for each pulse is calculated to $7 \cdot 10^7$. The gain in the multiplier at the voltage used is 10^5. The number of photoelectrons is thus 700. The root-mean-square deviation of this value is $\sqrt{700} \approx 26$ or approximately 4 per cent. From Fig. 2 a value of the total spread of approximately 5 per cent is obtained. It is thus evident that the spread is essentially dependent upon variations in the number of photoelectrons.

Through repeated measurements of this kind with polonium melted into the phosphor but with varying gains in the multiplier, different phosphors, multipliers, etc., the apparatus proved to be stable and to function satisfactorily. Fig. 2 also indicates the degree of accuracy and the resolving power to be expected in measurements of the energy of alpha-rays. It seems possible to determine the location of the peak with an accuracy of about 1 per cent.

If the small statistical fluctuations are disregarded, the monoenergetic alpha-particles thus give pulses of one and the same height. It is reasonable to assume that similar conditions exist for other ionizing particles, e.g., protons and electrons. This is naturally a prerequisite for the use of the scintillation counter in the measurement of energy.

The next question is: In what way is the pulse height dependent upon the energy of the incident particles. Broser and Kallmann[1] have demonstrated that for alpha-particles the pulse height is directly proportional to the energy. They changed the energy by slowing down monoenergetic alpha-particles in air of different pressures and subsequently studied the pulse height distribution for the different energies. Another way of deciding this question is to investigate the pulse height distribution of a source which emits alpha-particles of several different energies, for example ThX.

ThX was isolated from a solution of thorium chloride in the usual manner with ammonia. The solution of ThX obtained was evaporated in a crucible. At the bot-

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[1] I. Broser, H. Kallmann, Nature *163*, 20 (1949).

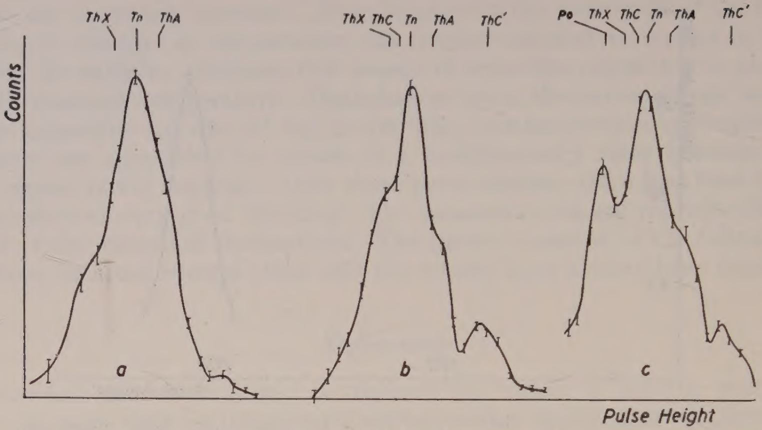

Fig. 3. Pulse height distribution curves for
a. alpha-rays from ThX immediately after the preparation of the source
b. alpha-rays from ThX 2 days after preparation of the source
c. alpha-rays from ThX + polonium.

tom of the crucible a small, unweighable amount of ThX was obtained. Sodium iodide and thallium nitrate were then melted in the crucible and a small crystal of natrium iodide was made. Part of the ThX was thus incorporated in the crystal. When this radioactive crystal was employed as the phosphor in the scintillation counter the pulse height distribution curve of Fig. 3 a was obtained. The fact that this curve is not as symmetrical as that of the measurements with polonium in Fig. 2 can be explained as follows. Immediately after isolation a ThX-source contains ThX, Tn, and ThA in radioactive equilibrium. In the phosphor alpha-particles of three different energies are thus emitted in equal amounts. For each one of these energies a symmetrical distribution according to Fig. 2 should be obtained. If the pulse height is proportional to the energy, the three peaks must be displaced in relation to one another. The pulse height distribution of the alpha-rays should thus be obtained by a combination of these three peaks. Since the energy values of ThX, Tn, and ThA lie fairly close together the peaks are not separated but merge into one peak.

The crystal of sodium iodide was then examined in the scintillation counter 2 days after being made. After this time the radioactive equilibrium comprises the two alpha-ray-emitting elements ThC and ThC′ as well. On account of the branching of the disintegration series these elements together have the same activity as any one of the other elements in the equilibrium. The equilibrium is composed of 35 per cent ThC and 65 per cent ThC′. The peaks corresponding to ThC and ThC^1 are thus not as high as those corresponding to the other elements, i.e., ThX, Tn, and ThA. The distribution curve is shown in Fig. 3 b. The pulses of the alpha-particles from ThC are only faintly indicated. The peak for ThC′, on the other hand, appears very clearly, and is suggested also in Fig. 3 a. During the time required for making the radioactive phosphor some new ThC′ is formed. The positions of the components on the distribution curve support the assumption that the pulse height is proportional to the energy.

A small amount of polonium was added to the melt of sodium iodide, containing

ThX and its disintegration products. A small sodium iodide crystal was made in the usual manner. This radioactive crystal was then examined in the scintillation counter. The pulse height distribution curve is seen in Fig. 3 c. It has the same form as the curve in Fig. 3 b, but there is one peak more corresponding to the alpha-rays from the polonium. This peak occurs where it might be expected if the pulse height is proportional to the energy.

Thus it seems possible to use scintillation counter for measuring the energy of alpha-rays. If the rays are monoenergetic or include only a few, well separated energies, a considerable degree of accuracy can be reached. If the difference in energy is too slight the limited resolving power permits only a measurement of the average energy. The resolving power, however, can probably be somewhat increased. As has previously been shown the decisive factor in this case is the number of photoelectrons. A large number of photoelectrons means a limited spread in the pulse distribution and therefore greater resolving power. One should thus strive to collect as much as possible of the light emitted from the crystal on the photo-cathode. The newest type of photomultipliers, 5819, is probably much better in this respect than 1 P 21.

The method of melting the radioactive material into the phosphor has the advantage of being very simple. It should be used particularly in analyses of weak sources. By measuring a pulse height distribution curve as demonstrated above, the composition of the sample can be determined, at least in some cases. It should also be possible in this way to determine the amount of radioactive material in a sample. This, however, would necessitate a closer study of how much of the radioactive material in the fused mass is incorporated in the crystal of sodium iodide at different concentrations, the effect of the other components of the sample, etc.

Gamma-rays

In a scintillation counter gamma-rays are counted by means of the electrons which are released in the phosphor on the absorption of the rays. It should be possible to determine the energy of the gamma-rays by measuring the energy of the electrons with the scintillation counter. The matter is complicated by the fact that the gamma-rays can be absorbed in three different ways: by the Compton effect, the photoelectric effect, and pair production. Pair production, however, can be disregarded for energies below 2 MeV.

If a phosphor with atoms of low atomic number is used, e.g., naphthalene or anthracene, the gamma-rays are practically entirely absorbed through the Compton effect. By measuring the energy of the recoil electrons with the scintillation counter one ought to be able to determine the energy of the gamma-rays. The recoil electrons of monoenergetic gamma-rays, however, possess all energies from zero to a certain maximal value, E_{max}. The number of recoils rises slowly to a maximum immediately below E_{max} after which it falls rapidly to zero. If E_{max} can be determined by means of the scintillation counter, the energy of the gamma-rays can be calculated. The object is thus to determine the maximal height of the pulses, i.e., the end point of the pulse height distribution curve. JORDAN and BELL[1] have recently reported some measurements in this manner. It can be rather difficult, however, to determine the end point with any accuracy, particularly since the scintillation coun-

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[1] W. H. JORDAN, P. R. BELL, Nucleonics *5*, No 4 (1949).

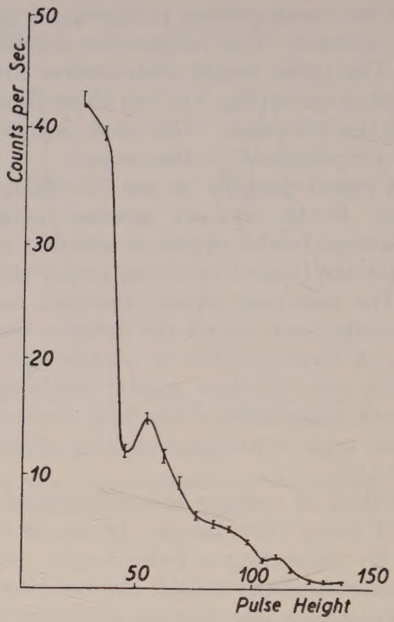

Fig. 4. Pulse height distribution curve for gamma-rays from ^{76}As.

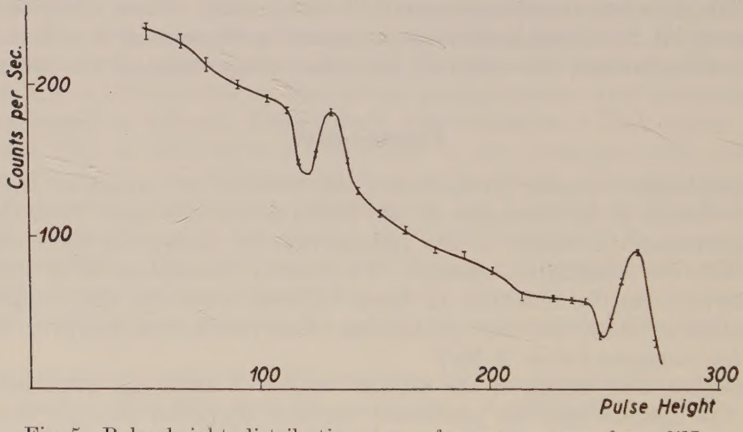

Fig. 5. Pulse height distribution curve for gamma-rays from ^{24}Na.

ter gives a statistical spread of the pulse height. This difficulty is noticed especially in gamma-rays with two or more adjacent energies.

The conditions are different if the phosphor is made of a substance which includes atoms of high atomic number, e.g., sodium iodide. The Compton effect still dominates the absorption of the gamma-rays within the energy range of 0.5 to 7 MeV, but a comparatively large number of photoelectrons are also emitted for energies up to 2 to 3 MeV. In the pulse height distribution curve the continuous distribution of recoil electrons is still obtained but there is also a peak corresponding to the monoenergetic photoelectrons. This is of advantage since it is easier to determine the position of a peak than the end point of a continuous distribution. Moreover, the

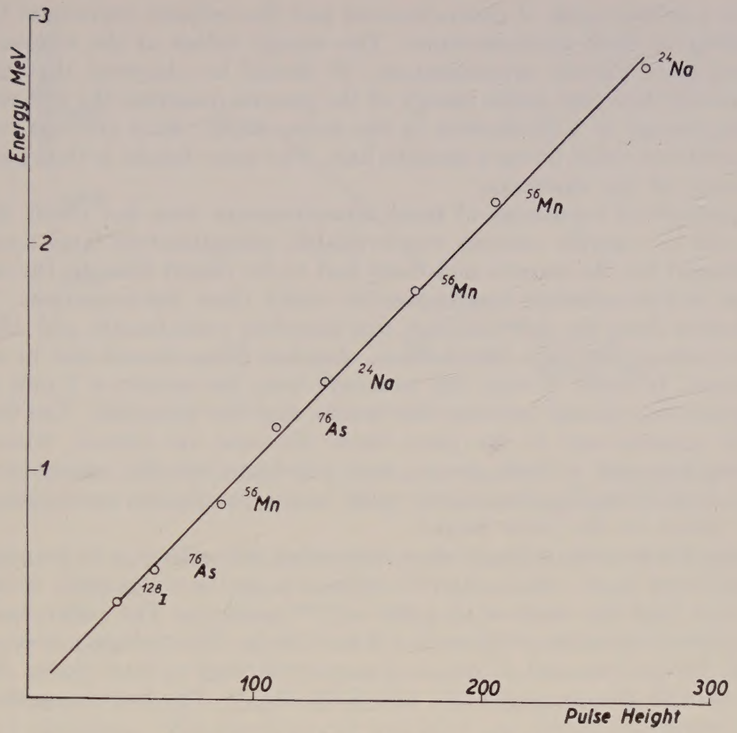

Fig. 6. Calibration curve. The energy of the photoelectrons is plotted against the corresponding pulse height.

statistical spread in the scintillation counter does not alter the location of the peak which only becomes broader. These advantages are particularly evident in sources with several adjacent gamma-rays.

Fig. 4 shows a pulse height distribution curve obtained with a weak source of ^{76}As. Between the source and the phosphor a 3 mm thick plate of aluminium was placed to stop the beta-rays emitted by the source. ^{76}As emits gamma-rays with the energies 0.55 and 1.25 MeV.[1] The intensity relation is 3 : 1. The two distributions of the recoil electrons are clearly seen in the figure, each followed by its peak of photoelectrons.

Fig. 5 presents the pulse height distribution curve for the gamma-rays from ^{24}Na obtained in the same manner as the foregoing measurement, with 3 mm of aluminium between the source and the phosphor. The two peaks correspond to the photoelectrons for the gamma-energies 1.38 and 2.76 MeV.

Some other gamma-ray emitting sources have been examined in the same way. In all cases peaks were obtained on the pulse height distribution curves, corresponding to the gamma-energies of the source under investigation. In order to use this method to measure gamma-energies, the dependence of the pulse height on the energy of the photoelectrons must be studied, i.e., a calibration curve must be drawn. Such a curve is shown in Fig. 6. The abscissa represents the pulse height corresponding to a certain peak of photoelectrons and the ordinate represents the energy corresponding to these photoelectrons. The energy values of the sources used are well known from various investigations. It should be observed that the photoelectrons do not have the entire energy of the gamma-quantum the difference being the binding energy of a K-electron in the iodine atom. It is obvious from Fig. 6 that the points recorded lie on a straight line. The pulse height is thus proportional to the energy of the electrons.

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[1] The energy values used in this paper are taken from MATTAUCH-FLAMMERSFELD, Isotopenbericht (Tübingen 1949).

The experimental conditions of these measurements were not ideal. Since only material with low specific activity was available, comparatively large amounts had to be employed for the sources and these had to be placed close to the crystal. A collimation of the radiation was impossible under these circumstances. The scattered radiation from the surroundings was therefore considerable and affected naturally the form of the pulse distribution. Another factor should also be taken into consideration. In order to stop the beta-rays from the source, a 3 mm thick aluminium plate was placed between the source and the phosphor. On the absorption of the gamma-rays in the plate recoil electrons are formed. Some of these, after having lost part of their energy, may penetrate into the phosphor. There is thus an addition of small pulses and the pulse height distribution curve rises markedly for small values in the pulse height.

If a pulse distribution without these disturbing side-effects is to be obtained the source used must be so strong that the radiation can be collimated. Some measurements were therefore made with a 300 mC ^{60}Co-source. The latter was enclosed in an aluminium container with walls 0.5 mm thick. The radiation was collimated in a canal, 16 cm long and 2 mm in diameter, through a lead block. ^{60}Co emits gamma-rays with the energies 1.171 and 1.332 MeV.[1] The two components are of the same intensity.

In these measurements the experimental conditions were varied in order to control that the pulse height distributions measured did not change through the substitution of phosphor or alteration of the voltage of the photomultiplier. The same result was obtained independently of these changes. Nor did a reconstruction of the pulse height discriminator alter the results in any way. On account of these variations the scintillation counter had to be calibrated before each measurement with ^{60}Co. The calibration was made with ^{24}Na. A distribution curve according to Fig. 5 was then obtained, with two peaks corresponding to the photoelectrons of the two energies in the radiation. From such a measurement with ^{24}Na two points on the calibration curve are obtained which is then easily drawn, as it is a straight line. This case is especially favourable as one of the energies in the radiation from ^{24}Na (1.38 MeV) lies close to the energy for the radiation from ^{60}Co. The calibrations make it possible to convert the pulse height into energy and to draw pulse height distribution curves with energies along the abscissa. One of the curves obtained is presented in Fig. 7. The two peaks corresponding to the photoelectrons of the two energies appear well separated. From their position the energy of the gamma-rays can thus be directly read. Three measurements made under different conditions gave the results 1.14, 1.34; 1.18, 1.32 and 1.15, 1.32 with the mean values 1.16 and 1.33 MeV. A comparison with the more exact values 1.171 and 1.332 MeV indicates that this method can be used to measure gamma-energies with considerable accuracy, in the present case approximately 1 per cent. The curve in Fig. 7 shows that

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[1] D. A. LIND, J. R. BROWN, J. W. M. DU MOND, Phys. Rev. *76*, 1838 (1949).

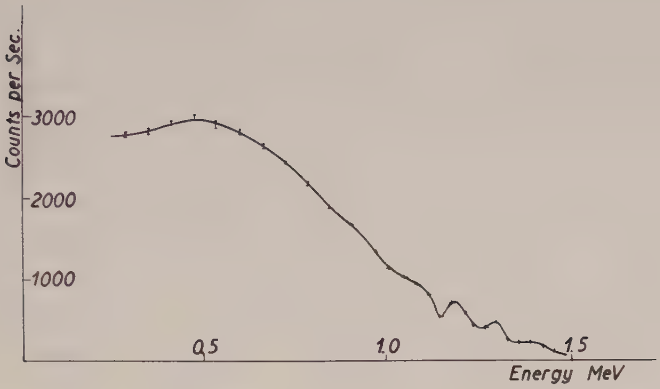

Fig. 7. Pulse height distribution curve for gamma-rays from ^{60}Co.

the resolving power is fairly good. It is probably possible to distinguish two energies with a difference of more than 0.07 MeV, provided they are of about the same intensity.

It is of great interest to know whether the linear relationship between pulse height and energy is valid also for higher energies. Gamma-rays from the reaction ^{19}F (p α', γ) were therefore examined. This radiation, which has been investigated several times, consists of a strong line with the energy of 6.13 MeV, and a weaker one with the energy of 6.98 MeV.[1] The protons were accelerated in a Van de Graaff generator. The accelerating voltage was 862 kV. At this proton energy the reaction has a strong resonance. Measurements of this kind are difficult as it is impossible to procure constant experimental conditions. The beam of protons is not constant in strength and direction. Small variations in the accelerating voltage produce large changes in the yield on account of the strong resonance. In order to eliminate the effect of these fluctuations on the measurements a thin-walled Geiger-Müller tube of aluminium was placed close to the scintillation counter. The tube was enclosed by an iron tube with walls 4 mm thick, to prevent that it counted the X-rays from the Van de Graaff generator. In the measurements the scintillation counter and the Geiger-Müller counter were started at the same time and stopped when a certain number of pulses had been obtained on the Geiger-Müller counter. In this way the number of pulses for different positions of the discriminator will always refer to one and the same total number of gamma-photons. The differential pulse distribution curve can be obtained from the differences between the number of pulses for adjacent settings of the discriminator. The curve is shown in Fig. 8. Prior to the measurements the counter was calibrated by means of gamma-rays from ^{60}Co. It was assumed that the proportionality between pulse height and energy is valid also for higher energies. With this extrapolated calibration curve the pulse height was converted into energy. The energy is given on the abscissa in Fig. 8.

It is rather difficult to interpret the details of the distribution curve presented. The form of the curve is determined mainly by the distribution of the Compton recoil electrons. On the absorption of the gamma-rays in the crystal at these high energies a considerable number of electron-positron pairs are also formed which may

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[1] R. L. WALKER, B. D. MCDANIEL, Phys. Rev. *74*, 315 (1948).

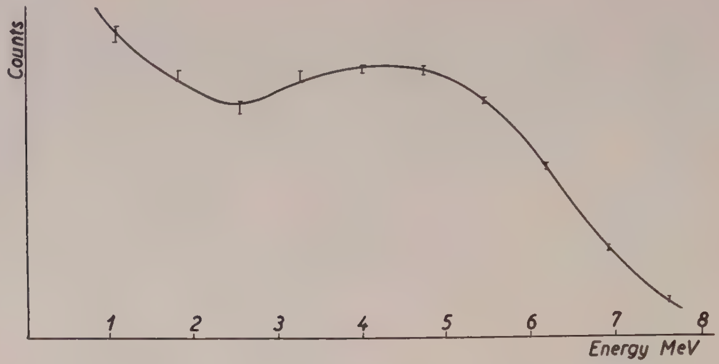

Fig. 8. Pulse height distribution curve for gamma-rays from the reaction $^{19}F\ (p\ \alpha', \gamma)$.

affect the shape of the curve. In addition, the recoil electrons with the greatest energy have a range of about 1 cm in the phosphor. This means that a considerable part of the electrons leaves the phosphor, thus giving up only part of its energy there. For this reason the distribution curves is somewhat deformed. Finally, the scattered radiation from the surroundings produces a marked rise for small energy values. The curve in Fig. 8 is fairly constant up to 6 MeV and thereafter declines abruptly. This fall evidently corresponds to the end point of the Compton distribution of the gamma-line 6.13. The portion of the curve lying above 6 MeV apparently arises from the weaker gamma-line 6.98. The energy scale employed is thus substantially correct. It follows that for electrons the pulse height is proportional to the energy up to energies of 6 to 7 MeV.

These measurements with gamma-rays of different energies show that it is possible with scintillation counter to measure the energy of gamma-rays with considerable accuracy. For the phosphor, however, one must use a substance containing atoms with a fairly high atomic number. The energy of the photo-electrons emitted on the absorption of the gamma-rays can then be measured by means of the scintillation counter with satisfactory accuracy. For gamma-rays with higher energy than 3 MeV the number of photoelectrons is insufficient. The maximal energy of the Compton recoil electrons must then be determined in order to find out the energy.

For measuring energies of gamma-rays, a scintillation counter has both advantages and disadvantages when compared with a beta-spectrometer. The resolving power of the scintillation counter is considerably inferior. A somewhat better resolving power than that obtained in the measurements described above can probably be reached. The great simplicity of the apparatus is an advantage. The greatest advantage, however, is the high sensitivity. On measuring the energy of the gamma-rays with a beta-spectrometer, the photoelectrons are ejected from a lead foil with a thickness of 10 100 mg/cm^2. In the scintillation counter the photoelectrons are emitted in the phosphor which has a thickness of up to 10 g/cm^2. In the beta-spectrometer a few per cent at the most of the electrons ejected reach the detector. In the scintillation counter all the photoelectrons are counted. With a scintillation counter it is thus possible to use sources of very low activity in measuring the energy of gamma-rays.

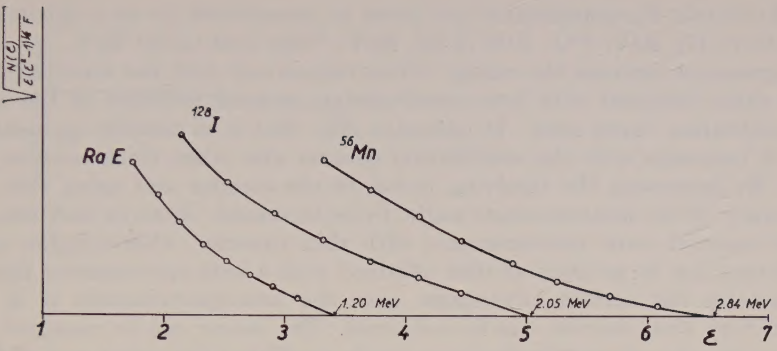

Fig. 9. Fermi diagrams for the electrons from RaE, ^{128}I and ^{56}Mn.

Beta-rays

The calibration curve shown in Fig. 6 should be utilizable also for measurements of the energy of beta-rays. Since the beta-rays have a continuous energy distribution, pulse heights from zero up to a maximal value are obtained by the scintillation counter. By determining this value the maximal energy of the beta-rays is obtained. On account of the statistical spread in the scintillation counter it is very difficult to determine the maximal pulse height directly. It is possible, however, to convert the pulse height into energy by means of the calibration curve after which a Fermi diagram may be drawn in the usual manner. From this diagram the maximal energy of the beta-rays can be determined.

In these measurements the beta-ray emitting substances RaE, ^{128}J, and ^{56}Mn were used. They emit also gamma-rays which necessitated a determination of the amount of gamma-rays that was absorbed in the phosphor and thus was counted together with the beta-rays. This determination was made by measurements in which the beta-rays were stopped in an aluminium plate.

Fig. 9 shows the three Fermi diagrams. The curving of the lines has several causes. Since only substances with low specific activity were at hand comparatively thick sources had to be used in order to obtain a sufficient counting rate. The self absorption and scattering in the source produced an excess of electrons with low energy, which caused a curving in the Fermi diagram. Moreover, the pulse height distribution as well as the Fermi diagram are influenced by the statistical distribution in the scintillation counter. It should be pointed out that RaE and ^{128}J do not give a linear Fermi diagram even with thin sources and when measured in a beta-spectrometer. This is due to the fact that the beta-rays from RaE[1] correspond to a forbidden transition and that the beta-rays from ^{128}J[2] have two components with about the same maximal energy. It is possible, however, to determine the maximal energies from Fig. 9 with fairly good accuracy. The uncertainty in the extrapolation is probably less than 3 per cent. From a number of measurements the following mean values for the maximal energies were obtained (corresponding values according to MATTAUCH-FLAMMERSFELD[1] are given in parentheses by way of comparison): RaE: 1.19 (1.17) MeV; ^{128}J: 2.04 (2.02) MeV; ^{56}Mn 2.82 (2.86) MeV.

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[1] A. Flammersfeld, ZS f. Physik *112*, 727 (1939).

[2] K. Siegbahn, N. Hole, Phys. Rev. *70*, 133 (1946).

The agreement between the energy values determined with the scintillation counter and those obtained with beta-spectrometers is good evidence of the accuracy of the calibration curve used. It indicates, too, that it is possible to measure the energy of beta-rays with the scintillation counter also when thick sources are employed. By increasing the resolving power of the counter and using thin sources the accuracy of the measurements ought to be increased. JORDAN and BELL[2] have recently reported some measurements with thin sources. Although the accuracy attained may not be so great as that obtained with a beta-spectrometer the scintillation counter has certain advantages over the beta-spectrometer: it is simpler and even very weak sources can be measured. The source can be mounted in such a way and the phosphor of such a form can be used, that the major part of the electrons emitted penetrate into the phosphor.

Cosmic rays

As has been mentioned before the background can be almost entirely eliminated by means of a suitable discriminator setting. There remains, however, a small number of pulses even when the discriminator is set on very great pulse heights. The number of these pulses, approximately 5 per minute, is constant over a large pulse height interval. These large background pulses have considerably greater height than the pulses of electrons with an energy of several MeV. They can, therefore, not be caused by the radiation from radioactive impurities in the surroundings of the counter. They might possibly arise from alpha-particles emitted by radioactive impurities in the phosphor itself. They may also be caused by ionizing particles in the cosmic rays. In order to demonstrate that at least some part of these pulses actually arise from the cosmic rays an apparatus according to Fig. 10 is employed.

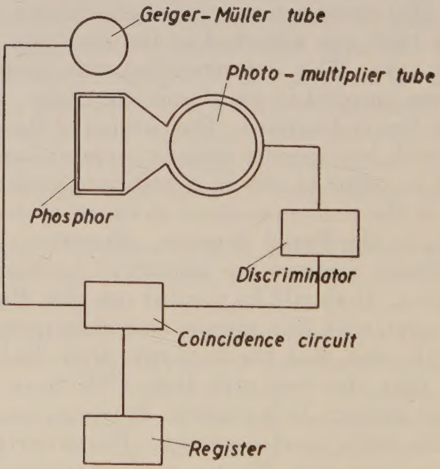

Fig. 10. Experimental arrangement for investigation of cosmic rays.

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[1] The energy values used in this paper are taken from MATTAUCH-FLAMMERSFELD, Isotopenbericht (Tübingen 1949).

[2] W. H. JORDAN, P. R. BELL, Nucleonics *5*, No 4 (1949).

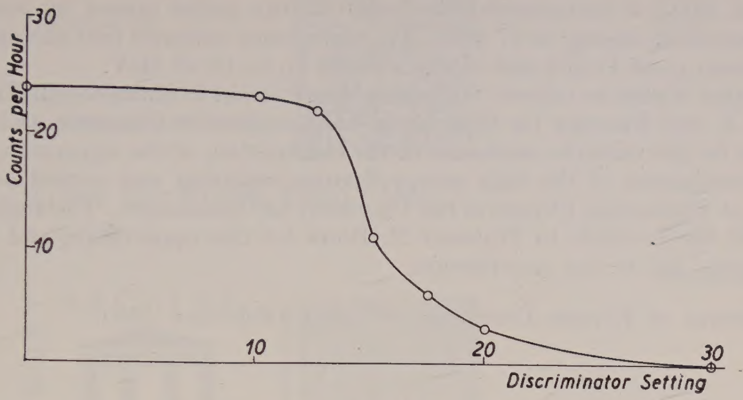

Fig. 11. Intergral bias curve for the cosmic ray pulses.

The scintillation counter is connected to a discriminator and that in turn to a coincidence circuit. Right above the phosphor a Geiger-Müller tube is placed. The quenching circuit of the tube is connected to the coincidence circuit. The apparatus thus records only those particles which pass through both the Geiger-Müller tube and the phosphor. On account of the low counting rate practically no accidental coincidences are obtained. One obtains approximately 20 pulses per hour with this apparatus. The fact that these pulses disappear completely if the Geiger-Müller tube is moved somewhat to one side proves that they are caused by cosmic rays.

By varying the discriminator setting the pulse height distribution can be studied. Fig. 11 shows the integral bias curve. It appears clearly from the curve that the pulses are of approximately the same height. This was to be expected if the pulses are caused by cosmic rays. In these measurements one does not obtain the energy of the particles but only their energy loss in the phosphor. The main part of the particles in the cosmic rays has an energy loss which is rather independent of the energy of the particles. Furthermore, the particles which are counted have paths of approximately the same length within the phosphor. The pulses from the counter should thus be of the same height.

It is possible to calculate the energy loss in the phosphor by applying the theoretic formulas[1] for the energy loss of ionizing particles on passing through matter and by considering the energy spectrum of the particles. For mesons which constitute the main part of the ionizing particles, an energy loss of 1.7 MeV cm^2/g is calculated. This is an average value, but since the energy loss only varies slightly with the energy, the deviations from the mean are quite small. For electrons somewhat higher and more varying values are obtained but since the electrons are fewer in number than the mesons they do not have as great an effect upon the pulse height distribution. The phosphor has a density of 3.67 g/cm^3 and the path of the particles within the phosphor is on the average 2.5 cm. The energy loss in the phosphor is thus calculated to about 16 MeV. This value can now be compared to the results of the energy measurements in the preceding section. Prior to the measurements the counter was calibrated with gamma-ray emitting sources as previously described. When this calibration curve is extrapolated the height of the pulses caused by cosmic rays corresponds to the energy of 17 MeV. This agreement indicates that the proportionality between pulse height and energy is valid up to 15–20 MeV.

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[1] B. Rossi, K. Greisen, Rev. Mod. Phys. *13,* 240 (1941).

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